Upper Ocean Response and Dynamics of the South China Sea and Ocean Internal Wave Database

Xiao-Hai Yan
Graduate College of Marine Studies
University of Delaware
Newark, DE 19716
Phone: (302) 831-3694 Fax: (302) 831-1199 Email: xiaohai@udel.edu

Victor V. Klemas
Graduate College of Marine Studies
University of Delaware
Newark, DE 19716
Phone: (302) 831-8256 Fax: (302) 831-6838 Email: klemas@udel.edu

Award #: N00014-03-1-0337
http://www.onr.navy.mil/sci_tech/ocean/onrpgahj.htm

LONG-TERM GOALS

The long-term goal of the project is to understand the response to atmospheric events and dynamics of marginal seas ranging from shallow waters with a depth of 100 m to the continental slope with a depth of over 1000 m, in particular, in the South China Sea (SCS). The second long-term goal is to develop a global database of ocean internal waves observed primarily from spacecraft. This database will be publicly accessible and can be used for various purposes including understanding the statistical properties of internal waves and upper ocean dynamics in any ocean area of interest.

OBJECTIVES

We have been focusing on the following scientific objectives:

1) To obtain the atmospheric variability over the SCS at interannual and intraseasonal scales.

2) To determine the response of the ocean dynamic processes to atmospheric forcing, and the effects of the SCS on monsoon variability.

3) To determine the effects of the SCS and monsoon system on the precipitation in the region and beyond.

4) To develop a multi-sensor approach for the analysis of the atmospheric and oceanic phenomena.

5) To apply a numerical model and data assimilation analyses on the upwelling along the western boundary of the SCS, the cold jet off the Vietnam coast, and the Kuroshio intrusion.

For the IW Database, our objectives are to extract information on ocean internal waves from Space Shuttle photographs and satellite SAR images, to construct a database containing the information for global oceans and to make the database publicly accessible via the Internet. We demonstrate the use of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Upper Ocean Response and Dynamics of the South China Sea and Ocean Internal Wave Database**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Graduate College of Marine Studies,,University of Delaware,,Newark,,DE, 19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The long-term goal of the project is to understand the response to atmospheric events and dynamics of marginal seas ranging from shallow waters with a depth of 100 m to the continental slope with a depth of over 1000 m, in particular, in the South China Sea (SCS). The second long-term goal is to develop a global database of ocean internal waves observed primarily from spacecraft. This database will be publicly accessible and can be used for various purposes including understanding the statistical properties of internal waves and upper ocean dynamics in any ocean area of interest.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

the database by performing statistical analyses of internal wave features and dynamic analysis of their evolution under continental shelf boundary conditions.

APPROACH

The approach to accomplish the above objectives is to emphasize the composite analysis of multi-sensor data from Quickscat, TOPEX/Poseidon and Jason, NOAA/AVHRR, and the results from data assimilating and numerical modeling. Our combined approach should generate patterns relating sea surface height, wind, and SST, which will aid in the simulation of the ocean response. The methods used include the vector empirical orthogonal function decomposition (VEOF), principal oscillation pattern (POP), coupled pattern analysis (CPA), and Hilbert-Huang Transform (HHT). The Princeton Ocean Model (POM) and Optimal Interpolating (OI) approach are used in the numerical modeling and data assimilating studies, respectively. The modeling work and the analysis of the satellite data are strongly connected. The satellite data are used to set the initial and boundary conditions and the model results significantly help interpret satellite observations. Field data includes the South China Sea Monsoon Experiment (SCSMEX) data set and Asian Seas International Acoustics Experiment (ASIAEX). The global database of ocean internal waves has two major sections, one for Space Shuttle images and a separate section containing SAR imagery from ERS-1, 2, Radarsat, and other spacecraft. The images are accompanied by interpretation maps and text describing oceanographic properties of the imaged features. The database includes a home page, offers a standard format and is accessible to Internet users.

WORK COMPLETED

This is a new project started on December 23, 2002. However, we already have made significant progress in our research. We have collected satellite multi-sensor and field data sets and analyzed the monsoon forcing variability over the SCS. We have identified the interannual and intraseasonal variability of the SCS, determined the response of the SCS to the monsoon wind forcing, and analyzed effects of the SCS on the precipitation in the surrounding region using the composite and statistical methods of the VEOF, POP and CPA. We have studied the long term variability of ITCZ and hydrological forcing features in the SCS. We have also determined the initial and boundary conditions for POM, and tested the POM model. For the IW database, we have expanded and upgraded the current internal wave database with new data including space shuttle photographs, SAR images, and imagery from other satellites. We have generated interpretive maps, quantitative data and information extracted from images, and boundary conditions collected by field measurements. We have determined comprehensive and statistical characteristics of internal waves, including spatial and temporal scales, kinematic and dynamic parameters, regional generation sources and boundary conditions including ocean circulation systems, wind fields, water depth, and bottom topography. We have provided services for database users including providing copies of images, interpretation results, related material and information upon request, as well as answering questions. In addition, we have publicized the database and linked it to major scientific web sites.

RESULTS

Major Scientific Results for South China Sea Multisensor Study:

1. Ocean Color Data Applications

1.1 Evidence of upstream and downstream solitary wavetrain coexistence in the real atmosphere From a true color image of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) onboard the Orbview-2 satellite, we observed two packets of orderly wave clouds on two sides of Hainan Island in the South China Sea (Figure in ppt file). A packet of 23 wave clouds stretches southward from the island. A second packet of more than 20 wave clouds stretches northeastward off the northeast coast of the island. The concave orientation of the wave cloud lines implies that both packets are propagating away from the island. A chart of geopotential height and velocity at 850 mb shows a southwesterly air flow over the island; hence the two wave cloud packets propagate upstream and downstream, simultaneously. Thus, we have found new evidence of the coexistence of both upstream and downstream solitary wavetrains generated in the real atmosphere by land topographic disturbances. Comparison with theoretical results supports this conclusion (Grimshaw and Smyth, 1986). The results will be published on *International Journal of Remote Sensing* (accepted). The attached SeaWiFS image (Figure in ppt file) will be published as a cover of the issue, in which the article is published.

1.2 SeaWiFS Observations of Upwelling South of Madagascar: Longterm Variability and Interaction with East Madagascar Current SeaWiFS data from September 1997 to November 2001 were used for studying the spatial and temporal variations of upwelling south of Madagascar. EOF analysis revealed that the seasonal variation of upwelling is not obvious from the time series of the amplitude of EOF1. However, one can distinguish that peak amplitudes occur in austral winter of each year except 1999 and in austral summer of each year except 2001. This points out that the mechanisms of induced upwelling may be different. Previous studies indicate that the upwelling may be induced by the EMC and local wind stress. Lutjeharms and Machu (2000) used the SeaWiFS image taken on 23 August 1998 to illustrate upwelling induced by the EMC. DiMarco et al. (2000) used sea surface temperature images taken from January to March 2000 to pointed out that the upwelling is concurrent with anomalously high wind stress over the region during that period. The EOF analysis may account for both situations. The spatial distribution of EOF2 shows the flow path of EMC. This also implies the pattern of the interaction between upwelling and EMC. From the amplitude of EOF3, one can identify a positive peak appearing in February 1998 when the onset of the 1997-1998 El Niño. This indicates that the upwelling can be enhanced 3% of the total variance by the onset of El Niño. EOF2 showsthe interaction between upwelling and EMC. We examined the time series of SeaWiFS images and found that there were wave-like patterns along the southern boundary of upwelling area. These patterns propagate southwestward or westward along the boundary. We interpreted this kind of wave motion as the shear wave caused by the interaction of upwelling and EMC. We further analyzed the interaction phenomena with the shear wave propagation theory to gain more understand the dynamics of the current induced upwelling. From scale analysis, we derived a dispersion relation of the shear waves. It shows that the phase speed of shear waves is dependent on the velocity structure of EMC. The position of peak velocity is located at 60 – 100 km south of the boundary of the upwelling area. This result is comparable with field observation. From the statistic analysis (EOF) and the dynamic analysis (shear waves), we gain new understanding of the variation of upwelling south of Madagascar and the interaction between the upwelling and the EMC. However, more *in situ* and satellite observations in this region are necessary to test these conclusions (accepted by *Deep Sea Research*).

2. SST and Altimeter Data Applications

Response of Vietnam Coastal Upwelling to the 1997-1998 ENSO event observed by multi-sensor data A series of NOAA (National Oceanic and Atmospheric Administration) satellite AVHRR (Advanced Very High Resolution Radiometer) sea surface temperature (SST) images taken during

summers of 1997 to 2000 was used to examine the interannual variability of upwelling along the western coast of the South China Sea (SCS). The empirical orthogonal function (EOF) analysis of the spatial variance for twenty-eight selected 3-day composite images was performed. The first gradient EOF mode shows an alongshore structure that is related to the strength variation and the north-to-south migration of the upwelling area. The second gradient EOF mode reveals a cross-shore SST gradient with cooler upwelling waters inshore and warmer waters offshore. The third mode appears to display two circulation patterns: one is in the north and the other one is in the south of the upwelling area. These three modes account for 37%, 15%, and 8% of the spatial variability of the SST data set, respectively. The EOF analysis also indicates the impact of the El Niño and the La Niña events on the upwelling phenomena. The gradient EOF mode-1 function shows that stronger upwelling occurred during the 1997 El Niño summer while weaker upwelling occurred during the 1998 La Niña summer. The gradient EOF mode-2 function shows that the cross-shore temperature gradient between coastal upwelling and offshore waters was smaller during the 1997 El Niño summer than that during the 1998 La Niña summer. Furthermore, from ERS-2 (European Remote Sensing Satellite) wind data we can see a positive anomaly of wind stress near the western coast of the SCS during the summer of 1997, but a negative anomaly during 1998. We can suggest that the stronger southwesterly monsoon during the 1997 summer would induce stronger upwelling and therefore stretched out the cold-water area offshore blurring the SST gradient in the cross-shore direction. The reversed situation with weaker upwelling and a higher cross-shore SST gradient occurred during the 1998 La Niña summer. The EOF mode-1 also reveals that the upwelling had a clear north-to-south migration during the 1997 summer. These results are confirmed by TOPEX/POSEIDON and ERS altimeter data (submitted to *Remote Sensing of Environment*).

3. Numerical Model Testing

We have tested the POM for the SCS. We used Levitus 94 annual climatological potential temperature and salinity data to initialize the model and spun-up the model from rest with monthly climatological wind stress from ERS-1/2, heat flux from COADS with relaxation to AVHRR SST (pentad climatology) and salt flux based on relaxation from Levitus 94 monthly salinity, to obtain model climatological data, and correlations between the surface and the subsurface. Then realistic time-series data will be input to make nowcast and forecast running. Figures 1 and 2 show model temperature and velocity at 20m depth in mid-September and mid-January, respectively. In September, a transitional period from summer monsoon to winter monsoon, strengthening northeasterly winds control the northern SCS, while weakening southwesterly winds still dominate the southern SCS. Accordingly, anticyclonic circulation exists in the southern SCS, driven by southwesterly winds, while cyclonic circulation in the northern SCS, driven by both northeastly and Kuroshio intrusion. In the central SCS, these two circulation confluence and form a zonal current jet. There is a strong oceanographic front, north of which the water is colder and saltier, while south of which the water is warmer and fresher. In January, the basin scale circulation is cyclonic, driven by the strong northeasterly winds and Kuroshio intrusion. There is a strong southward alongshore current off the Vietnam coast.

4. New Internal Wave Study for South China Sea and Internal Wave Data Base

On a SPOT-3 visible image taken over the South China Sea continental shelf on July 24 1998, we observed two contrasting signatures of internal solitary waves (ISWs): darker stripes leading brighter stripes in the lower part, while brighter stripes leading darker stripes in the upper part. We suggest that the contrasting patterns are caused by ISWs of different polarities. A packet of ISWs is observed in the process of converting polarity from depression to elevation as a result of the bottom shoaling, both in

the propagation direction and in the transect direction. The evolution process can be obtained by transferring information from the spatial domain to the temporal domain. We find that the conversion process starts with the original depression ISWs passing the 160 m isobath. The total conversion time is about 4.6 hours. According to the oceanic stratification settings, we verified that the conversion process can be divided into two phases: the first is the flattening of the original depression ISWs and the second is the appearance of newborne elevation ISWs (accepted by *GRL*). An updated map of the global distribution of ocean internal wave cases in the expanded database and an updated entry page with the newly adopted "clickmap" search method can be accessed via the internet on the website http://atlas.cms.udel.edu. From there users can easily browse the whole database using their own machines.

IMPACT/APPLICATION

In this project, we emphasize the application of satellite multi-sensor data to study the upper ocean dynamics and oceanic response to the wind system forcing. The multi-sensor technique will be further developed by merging different data sets, numerical model and data assimilation results. The research will promote applications of satellite data to atmospheric and oceanic studies. The further understanding of the monsoon forcing variability over the SCS will lead to a better knowledge of climate in the surrounding areas and mesoscale dynamics of the SCS, and it will have significant impacts on the tele-forcing study of the US summertime droughts and floods. Our project also advances the utilization of remote sensing data. We demonstrate that multi-sensor data including space shuttle photographs and satellite SAR may serve as an important resource for high resolution observations of various ocean phenomena, in particular for remote ocean areas, which are sparsely investigated and located far away from the fields of view of ground station antennas used by other earth observing satellites. When completed, the Internet-accessible database will represent the largest collection of internal wave imagery observed by spacecraft over most of the globe. The sample size will be large enough for scientists to evaluate the general statistical properties of internal waves in various parts of the oceans. Furthermore, it will be possible to test models and obtain detailed descriptions of internal waves at specific ocean sites.

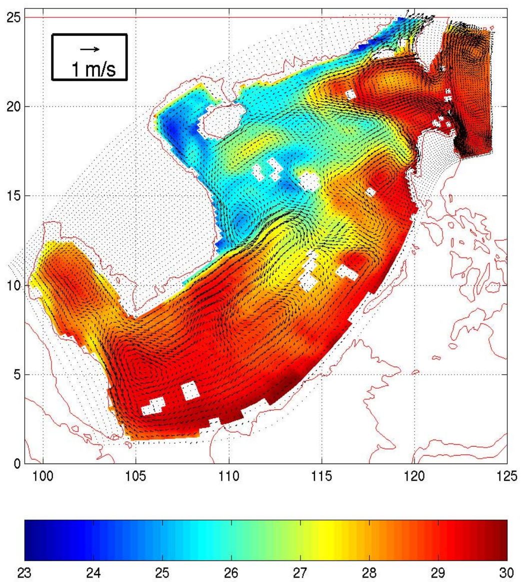

Figure 1. SST distribution and current velocity at 20 m depth in the SCS generated by the POM in mid-September after 3 year running.

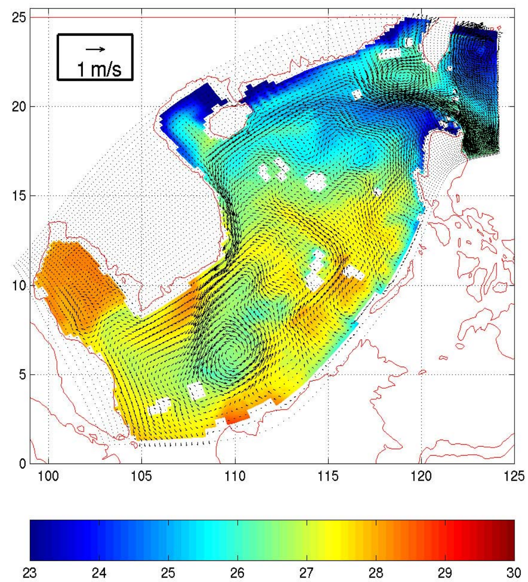

Figure2. SST distribution and current velocity at 20 m depth in the SCS generated by the POM in mid-January after 3 year running

TRANSITIONS

Scientists from various institutions have already requested imagery from our internal wave database. Eight papers using the data from this database have been published in scientific journals and at conferences.

RELATED PROJECTS

We have been working closely with various investigators, including Chris Jackson (Dr. John Apel's assistant at Global Ocean Associates), Dr. Antony Liu (NASA/GSFC), Tim Donato (NRL), et al. who have provided us with SAR imagery and performed some of the analyses in the SCS.

REFERENCES

DiMarco, S. F., Chapman, P., Nowlin, W. D., Jr., 2000. Satellite observations of upwelling on the continental shelf south of Madagascar. *Geophysical Research Letters* 27, 3965-3968.

Grimshaw, R. H. J., and Smyth, N., 1986, Resonant flow of a stratified fluid over topography. *Journal of Fluid Mechanics,* 169, 429-464.

Lutjeharms J. R. E., Machu, E., 2000. An upwelling cell inshore of the East Madagascar Current. *Deep-Sea Research I,* 47, 2405-2411.

PUBLICATIONS

The following publications during FY 2003 are supported or partially supported by this grant:

Yan, X-H., J. Pan, M. He, T. Liu and J. Young, 2003, Role of Wind on the estimation of Heat Flux Using Satellite Data. *J. Geophys. Res*. [refereed]

Yan, X.-H., Jo, Y., Liu, W.T. and M. He, 2003. Multi-Sensor Study of the Mediterranean Outflow and Meddies at 1000-Meter Depth, *J. Geophys. Res.* [refereed]

Liu, Y., X-H. Yan and Su, M-Y., Directional spectrum of wind wave: Part I-model and derivation, *J. Oceanic and Coastal Sea Research,* 2 (1): 1-12, 2003 [published, refereed]

Liu, Y., X-H. Yan and Su, M-Y., Directional spectrum of wind wave: Part II-comparison and confirmation, *J. Oceanic and Coastal Sea Research,* 2 (1): 13-24, 2003 [published, refereed]

Pan, J. X.-H. Yan, Q. Zheng, W. T. Liu, and V. Klemas. 2002. Interpretation of Scatterometer Ocean Surface Wind Vector EOFs in the Northwestern Pacific. *Remote Sensing of Environment*, 84: 53-68 [published, refereed]

Pan, J. X.-H. Yan, Q. Zheng, and W. T. Liu. 2002. Observation of Western Boundary Current Atmospheric Convergence Zones Using Scatterometer Winds. *Geophysical Research Letters*. 29, 1832-1853 [published, refereed]

Pan,J., X.-H. Yan, Jo,Y.-H. and Liu,W.T., 2003, A new method for estimation of the sensible heat flux in the unstable condition using satellite vector winds, *J. Phys Oceanogr.*. [in press, refereed]

Ho, Chung-Ru, Quanan Zheng, and Nan-Jung Kuo, 2003, SeaWiFS observations of upwelling south of Madagascar: Longterm variability and interaction with East Madagascar Current, *Deep-Sea Research*, [in press, refereed]

Kuo, Nan-Jung, Quanan Zheng, and Chung-Ru Ho, 2003, Response of Vietnam coastal upwelling to the 1997-1998 ENSO event observed by multi-sensor data, *Remote Sensing of Environment,* [refereed]

Zheng, Q. Samuel S. P. Shen, Yeli Yuan , Norden E. Huang,Victor Klemas, Xiao-Hai Yan, Fengyan Shi, Xuebin Zhang, Zhongxiang Zhao, Xiaofeng Li, and Pablo Clemente-Colón, 2003, Evidence of upstream and downstream solitary wavetrains coexistence in the real atmosphere, *International Journal of Remote Sensing*, [in press, refereed]

Zhao, Z., V. Klemas, Q. Zheng, and X.-H. Yan, Satellite observations of internal solitary waves converting polarity, Geophysical Research Letter, 2003, [in press, refereed]

Zhao, Z., Nonlinear evolution of internal waves in the South China Sea, Dissertation, University of Delaware, 2003.

Zhang, X. and X.-H. Yan, Numerical modeling of the upper circulation in the South China Sea, J. Physical Oceanography 2003, [refereed]